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A Manufacturing Process for Precision Gold Support Rings for Laser Targets

Matthew Bono, Robin Hibbard

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OVERVIEW

A research effort performed by the Target Fabrication Group has developed a method for producing precision, meso-scale gold support rings for laser targets. Many different laser targets consist of planar components that are built upon a gold support ring, such as the HyDiv and RadG targets shown in Figure 1. Because of the sequence in which laser targets such as these must be built to achieve the required overall precision, the washer-shaped support rings must fit precisely onto fixtures that are used throughout the manufacturing process. Because the support ring is the fundamental structure onto which the target is built, any imprecision in the support ring propagates through the entire target. Thus, even if the physics performance of a laser target does not require a flat and precise support ring, the manufacturing methods used to achieve the overall level of precision demanded in the targets rely heavily on the precision of the support rings. Past efforts to purchase gold support rings from outside vendors have been either extremely costly, or the vendors were unable to deliver acceptable parts. On several occasions, difficulties in obtaining acceptable support rings in a timely manner have compromised the ability to manufacture and deliver targets in time for the shot dates. Because of the nature of laser target campaigns, where target designs are often finalized only a few months, or even weeks, before the shot date, it is often risky to rely on external vendors to supply these components. The risk can be eliminated with a manufacturing method that makes it reasonable to fabricate precision support rings ourselves. This document describes a manufacturing plan that was developed by the Target Fabrication Group for “mass producing” precision gold support rings that meet the requirements necessary for fabricating precise laser targets in a timely manner.

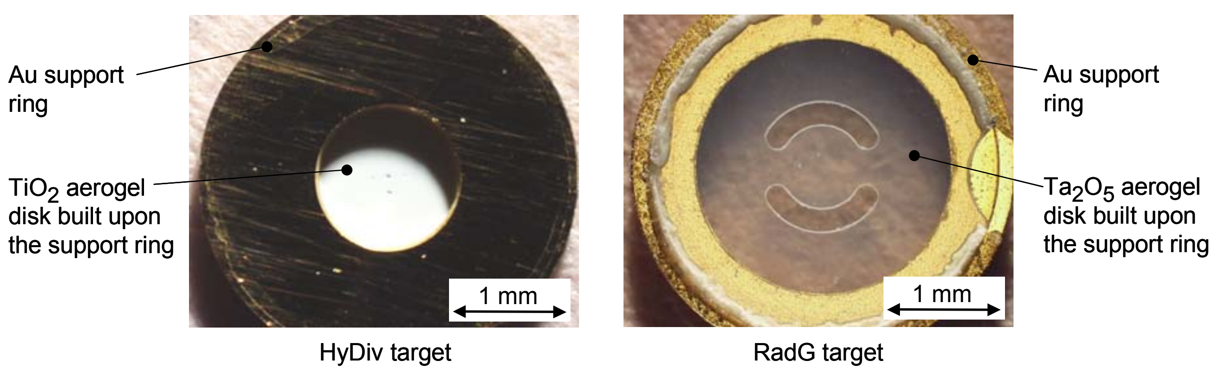

Figure 1. Examples of laser targets that are built upon gold support rings

Past efforts to manufacture or purchase precision support rings have met varying levels of success. Many laser target assemblies require rings made of pure gold with a thickness on the order of 100 μm to 200 μm. The support rings must be flat to within 2 μm (flatness/diameter = 0.04%), and the inner diameter must be precise to within approximately 1 μm to 2 μm (0.02% to 0.04%). The two faces of the ring must also be parallel and be free of surface contaminants. One method of producing high-quality rings is to diamond turn each one individually from a bar of stock material. This method produces rings with adequate flatness and dimensional accuracy, but it requires a great deal of time, so it is very expensive and ties up fabrication resources for a prohibitively long period of time. Another method that yields high-quality support rings is to plate gold onto a diamond turned copper mold. When the copper mold is etched away, a freestanding ring is produced. This method is also extremely time intensive and expensive. Efforts at both LLNL and by external vendors have attempted to produce gold support rings using various combinations of laser machining, wire EDM, turning, double sided lapping, and grinding. However, none of these other efforts produced acceptable support rings; the rings either did not meet the size specifications, did not meet the flatness and/or thickness specifications, or had large burrs on the edges. Prior campaigns with HyDiv and RadG targets required that a separate fixture be custom fit to each ring, which consumed a great deal of machining resources and delayed the delivery of the completed targets.

The new method developed in this research produces support rings using a combination of electroplating, diamond turning, milling, and etching. These support rings meet the specifications of 2 μm flatness and 2 μm precision in the inner diameter. Each batch of up to 100 precision support rings can be produced in a matter of days, and they are not limited to an axisymmetric shape. For example, support rings have been produced for EOS targets with an integral tab used for a mirror mount. Thus, this new method of producing support rings will not only increase the precision of the targets and eliminate potential compromises to their timely delivery, but it will also allow greater complexity in the design of target components.

MANUFACTURING STRATEGY

Before beginning this research effort in earnest, a quick initial trial was performed to identify potential issues with the planned manufacturing process. This initial test for manufacturing gold support rings began with a mandrel made of OFHC copper, which was fabricated by an external vendor. The mandrel was electroplated with a layer of gold, which was diamond turned to a thickness of 100 μm and a mirrored surface finish. The gold was then coated with a layer of copper with a thickness of 100 μm, which created a layer of gold sandwiched between layers of copper. The mandrel was then placed on a precision diamond turning machine, and a milling cutter was used to machine circular patterns through the gold layer that corresponded to the inner and outer diameters of several rings. The inner diameter of each support ring was 2.25 mm, and the outer diameter was 5 mm. As expected, the milling process created burrs on the surface of the copper overlay, but no burrs formed in the gold. The mandrel was then placed in an acid solution that dissolved the copper and left freestanding gold rings.

The support rings produced in this initial test had precise inner and outer diameters. However, the rings had flatness errors of 5 to 10 μm (flatness/diameter = 0.1% to 0.2%), which exceeded the desired value of 2 μm. Information gained in this initial test indicated several steps that could be taken to achieve flatter support rings. The flatness errors in the support rings indicated that stresses had been induced into the gold during either the electroplating, diamond turning, or milling. Upon etching away the rigid copper support structure, the residual stresses in the gold could cause the rings to deform and assume a warped shape. Therefore, it was hypothesized that a heat treatment could be used to remove any residual stresses in the gold prior to etching away the copper. This initial test also raised the question of the effectiveness of the copper overlay. The purpose of the copper coating was to prevent any burr from forming in the gold; instead, the burr would form at the free surface of the copper. However, it was not known if the additional plating process would adversely affect the stresses formed in the gold. Finally, the parameters used during the electroplating of the gold, such as the current density, were known to have an effect on the stresses in the gold. Based on this initial test, a set of experiments was designed to examine some of these issues in an attempt to achieve support rings with a flatness of 2 μm or better.

EXPERIMENTAL METHOD

A set of experiments was performed to identify an appropriate heat treatment cycle to relieve any stresses in the gold prior to dissolving the copper, which would result in flat, freestanding support rings. However, heat treating adjacent layers of gold and copper is complicated by the fact that gold and copper atoms interdiffuse very readily to form an alloyed, solid solution. Therefore, the heat treatment cycle must reach a temperature that is high enough to allow the gold atoms to diffuse to a stress-relieved condition, but the temperature must not be so high that copper-gold alloying becomes prevalent. One way to reduce the interdiffusion of copper and gold is to deposit a layer of nickel between them. Because nickel does not mix as readily with either copper or gold, the nickel acts as a diffusion barrier. Two different mandrels were prepared for the experiments. One of the mandrels consisted of a layer of gold surrounded by copper, as described above. The other mandrel was prepared with a layer of nickel with a thickness of several μm on either side of the gold. Because it was not known if the copper overlay would have any effect on the process, one half of each mandrel was masked during the plating of the upper nickel/copper layer. Therefore, the two mandrels contained four different types of workpieces, as illustrated in Figure 2. The following section of this report provides a detailed description of how these mandrels were processed to test various parameters.

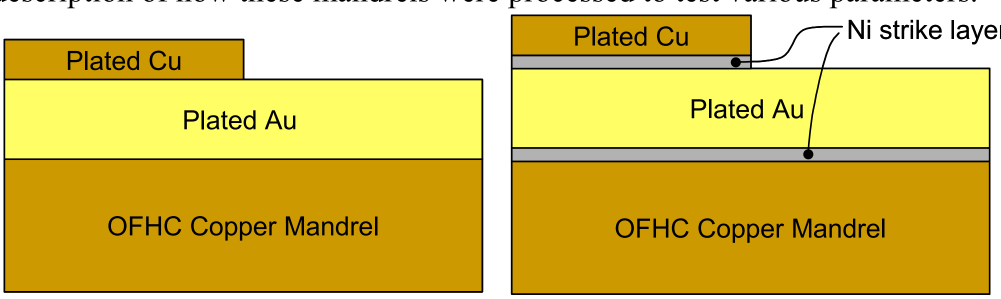

Figure 2. Side view of coated mandrels with (right) and without (left) a layer of Ni between the Au and the Cu

Processing the Mandrels

An illustration of an unprocessed copper mandrel appears in Figure 3. The mandrel had a thickness of 8.1 mm, and the upper face had a diameter of 72.6 mm. Three counter-bored bolt holes centered on the mandrel allowed it to be bolted against the face of the spindle of a precision diamond turning machine. The mandrel contained two reference surfaces that allowed it to be located onto the spindle of the machine tool with sub-μm repeatability. Before placing the mandrel on the spindle, the back face was lapped to make it flat. Then it was bolted in place on the spindle, the upper face and each of the reference surfaces were diamond turned so that they were flat with a mirrored surface finish. Next, the bolts were removed, and the mandrel was taken off of the machine tool.

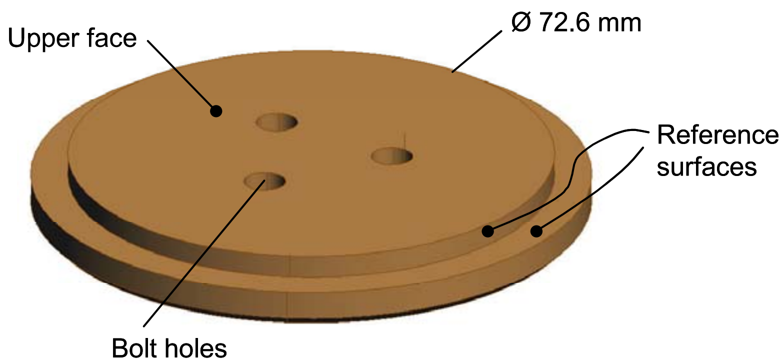

Figure 3. Copper mandrel

The mandrels were then prepared so that they could be electroplated with gold. First, the back surface and the reference surface were masked to prevent them from being covered with gold. The surfaces were masked with either plastic tape or polymer paint, and rubber stoppers were inserted into the counter-bored holes to prevent gold from coating the inner surfaces. One of the mandrels was then coated with a few µm of nickel to act as a diffusion barrier between the gold and copper during heat treatments. Each mandrel was then placed into the electroplating solution, so that a layer of gold coated the diamond turned upper face. The thickness of the electroplated gold layer was slightly larger than the desired thickness of the support rings. In this case, the desired support ring thickness was 100 µm, so approximately 150 µm of gold was deposited.

Various plating techniques were studied in order to attempt to minimize the stress induced in the gold during the plating process, as described in Reference [1]. The method that worked best used Techni-Gold 25 E plating solution at a temperature of 49 °C (120 °F). Each mandrel was carefully cleaned and then immersed in the solution and plated using a current density of 5 ASF. To achieve uniform plating, the solution was agitated during the process. When the electroplating was complete, the masking material was peeled off of the mandrel.

The gold plated mandrel was then placed back on the diamond turning machine. An indicator was run along the reference face of the mandrel to ensure that the lapped surface was properly seated against the face of the spindle, such that when the mandrel was rotated, the maximum wobble was less than 2 µm. A diamond tool was then touched to the reference surface to establish a workpiece coordinate system, and the gold coating was diamond turned to the final thickness. Unfortunately, due to wear of the diamond tool, the tool had to be changed while machining the gold on the mandrel with the nickel strike layer, and additional gold had to be removed to obtain an adequate surface finish. Therefore, the mandrel with the nickel strike contained a gold layer with a thickness of 78 µm, and the other mandrel contained a gold layer with a thickness of 100 µm.

The mandrel was then removed from the diamond turning machine, and the back surface and reference surfaces were masked again. One half of the upper face was also masked on each mandrel, so that subsequent plating would only cover the exposed portion. The mandrel with the nickel strike between the copper and the gold was then given another nickel strike on top of the diamond turned gold. Then approximately 200 µm of pure copper was coated onto the faces of the mandrels. At this point, the two mandrels had the configuration illustrated in Figure 2.

Milling the Washers

The coated mandrels were then ready to be milled to produce the target support rings. To mill a set of support rings in each mandrel, the mandrel was placed back on the spindle of the diamond turning machined, and a precision high-speed spindle was placed onto the tool holder, as illustrate in Figure 4.

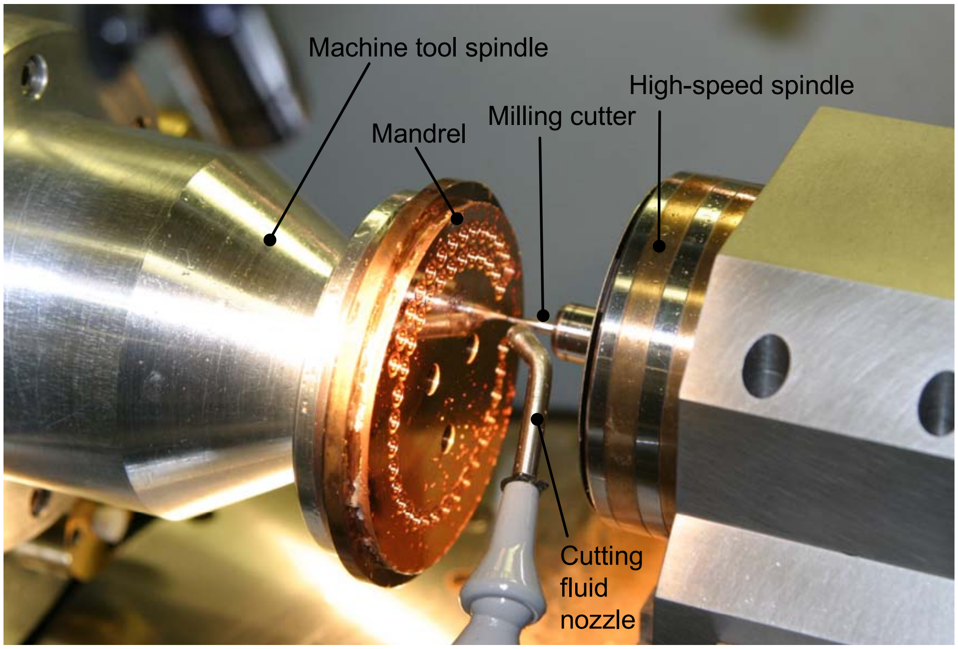

Figure 4. Setup of the mandrel on the machine tool spindle during the milling of the support rings (This picture was taken during a production run that produced over 100 precision support rings on the mandrel)

A two-fluted carbide milling cutter with a diameter of 762 μm (0.03") was inserted into the collet of the high-speed spindle. The x-axis, z-axis, and c-axis (the primary spindle axis) of the diamond turning machine were then used to move the mandrel relative to the milling cutter to machine out a pattern of rings. Each ring was machined by plunging the tool into the workpiece to a depth of 400 μm, and then machining a circle that formed the 5 mm outer diameter of the support ring. Next, the endmill was pulled out of the workpiece, and it then plunged back into the workpiece to machine a smaller circle concentric to the first circle, which formed the 2.25 mm inner diameter of the support ring, as illustrated in Figure 5. For this milling process, the high-speed spindle rotated at 10,000 rpm, and the radial feed per tooth was 3 μm.

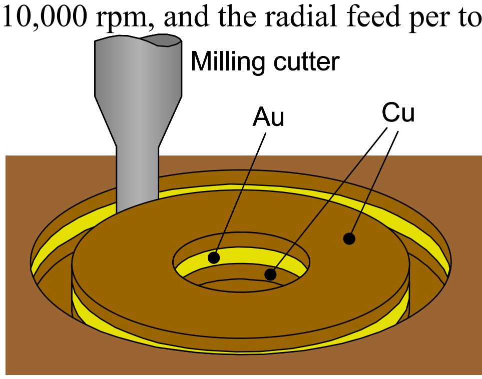

Figure 5. Milling of the inner and outer diameter of each ring

A pattern of support rings was machined in each mandrel to form 6 sets of 5 rings, as illustrated in Figure 6. After milling the forms of each of the rings, each mandrel was cut into 6 pieces using a wire EDM process. Each pie-shaped piece could then be subjected to a different heat treatment, before dissolving away the copper and nickel to yield 5 support rings.

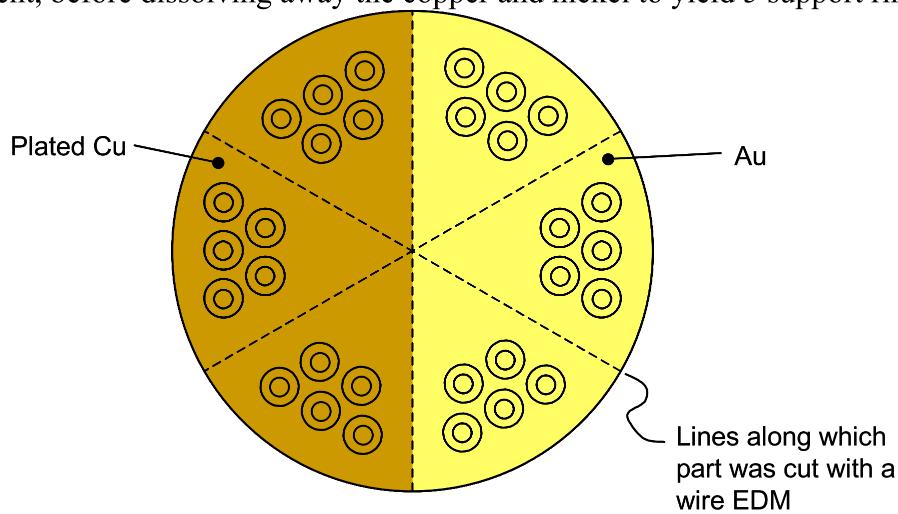

Figure 6. Pattern of 6 sets of 5 target support rings machined into each mandrel

Heat Treatment and Etching

Each pie-shaped piece was subjected to a different heat treatment in an attempt to alleviate any residual stresses in the gold prior to dissolving away the copper. Various heat treatments were tested for each type of specimen. One of the pieces from each of the four groups was treated as a control specimen, and was not given a heat treatment. These pieces were simply held at room temperature (21 °C). The other two pieces of each group were subjected to heat treatments. The heat treatments were done one at a time, using the results of the previous trials to select the temperature. The starting point for the heat treatment experiments was the recommended temperature for stress relieving metal parts, which is approximately 50% of the melting temperature, or 396 °C for gold. Using 396 °C as a starting point, various iterations were attempted to achieve flat support rings.

All heat treatment was done in a Barnstead Thermolyne 48058 benchtop furnace. For each heat treatment cycle, the part was placed into the furnace, which was then brought to the appropriate temperature. This temperature was maintained for 60 minutes, and then the furnace was deactivated so it could gradually cool back to room temperature overnight.

After cooling to room temperature, each pie-shaped piece was placed in Macrobrite L-7 solution, which contains 20-30 wt% chromic acid, 5-15 wt% acetic acid, and 5-10 wt% nitric acid. The acid solution dissolved the copper and the nickel, but it had no effect on the gold. This acid solution was deliberately selected to gently and slowly etch away the copper, in order to avoid any potential temperature effects that could arise from a harsher process. This etching process required approximately 48-72 hours to free the 5 gold support rings from the pie-shaped piece of the mandrel. Each of the support rings was then rinsed before being measured.

Metrology

Each profile of the face of each gold support ring was measured using a Wyko NT8000 optical profiling system. Measurements were made using VSI mode with a VSI filter and a modulation threshold of 4%. To make the measurements, a 5× objective was used with a 0.55× field of view. At this magnification, the total field of view of the system is 1.8 mm × 2.4 mm, which is several times smaller than the 5 mm diameter of the support rings. To measure the flatness of the entire ring, the data stitching feature of the Wyko system was used, where the stitching overlap was set to 40%. In this manner, the profile of each support ring could be measured accurately.

RESULTS AND DISCUSSION

Flatness of the Washers

Figure 7 contains a plot of the data collected in a typical, stitched measurement from the Wyko system. The bowed, axisymmetric shape of this support ring is typical of most of the support rings produced. Figure 8 contains a profile trace taken through this dataset and reveals that the flatness of this particular support ring is 1.5 μm.

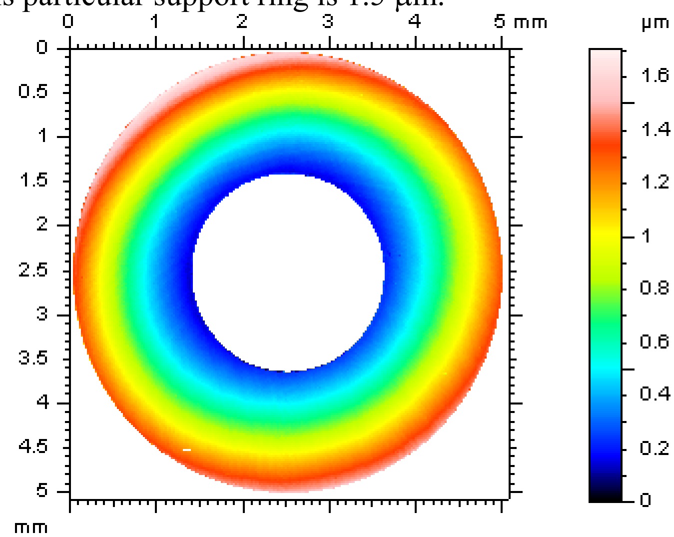

Figure 7. Wyko measurement of the profile of a support ring

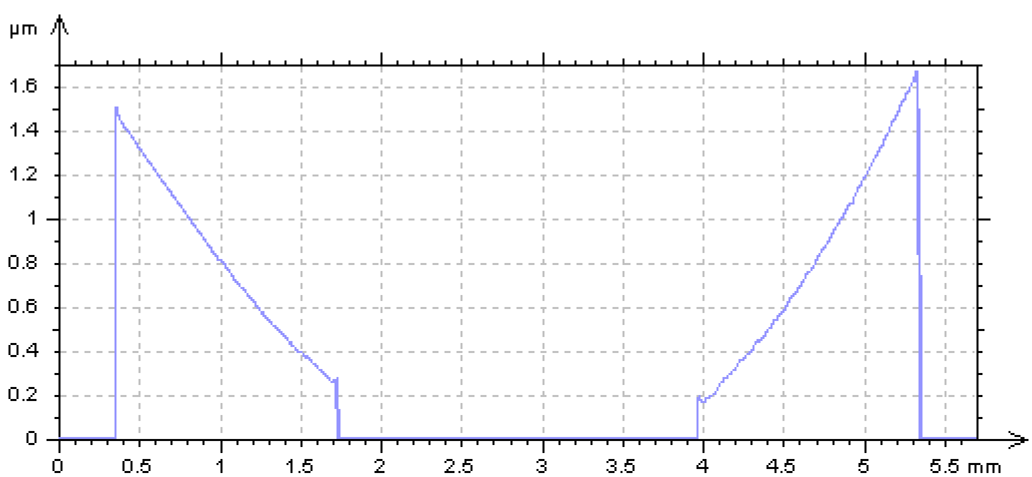

Figure 8. Profile trace through the Wyko dataset

Figure 9 and Figure 10 contain graphs of the flatness measured for each of the support rings made from the two mandrels. Figure 9 corresponds to the mandrel for which the gold was plated directly on the copper mandrel. The data points labeled “Cu-Au” represent the support rings machined from the section of the mandrel that did not have an overcoat of copper on top of the plated gold. The data points labeled “Cu-Au-Cu” represent the support rings machined from the section of the mandrel for which an overcoat of copper was plated on top of the gold. The dashed green line represents the specification of 2 μm flatness. Thus, the data points that fall below this line correspond to support rings that meet the specification.

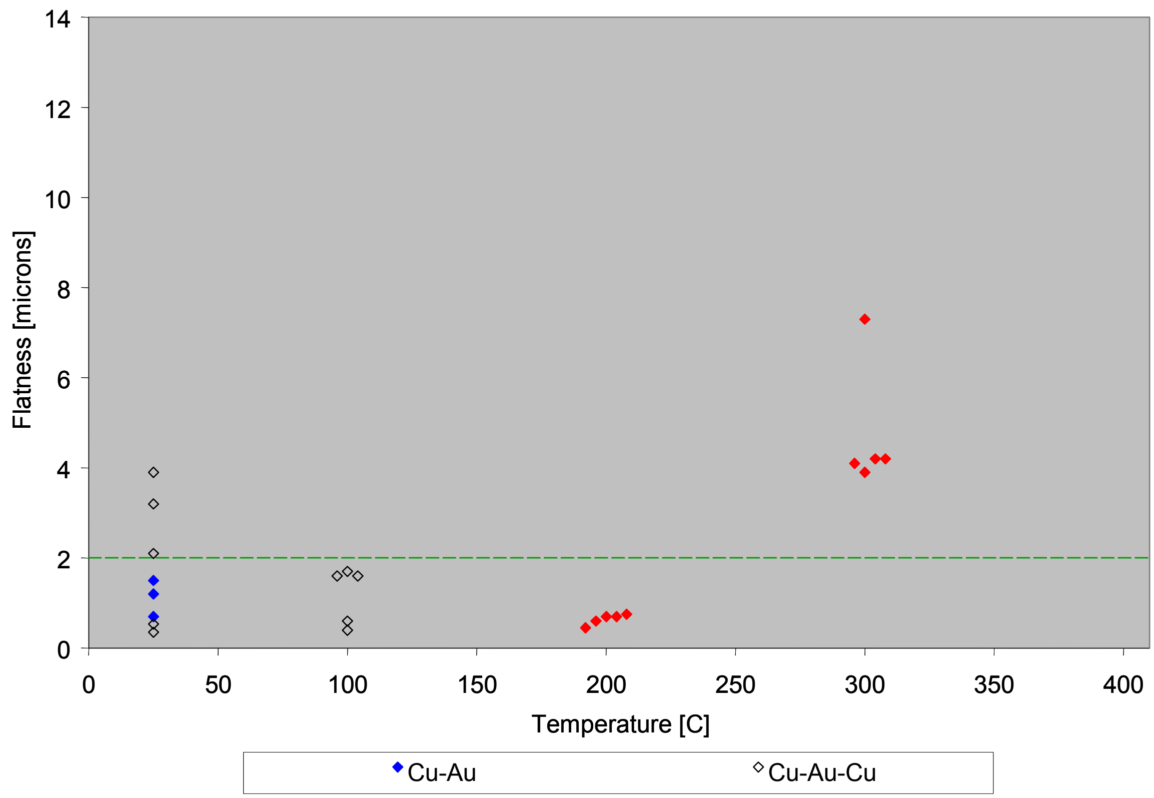

Figure 9. Flatness measurements for each of the rings from the mandrel with gold plated directly onto the copper mandrel

The red data points in Figure 9 indicate support rings that exhibit interdiffusion between the gold and the copper. The amount of interdiffusion varied with the heat treating temperature. The heat treatment at 200 °C caused only a slight reddish tint on the gold rings, but heat treatments at higher temperatures resulted in support rings with very rough surfaces. One batch of support rings was heat treated at 396 °C, but after etching away the copper, these support rings were so rough that the Wyko system could not measure them. Thus, the flatness of these support rings could not be determined, and they are not plotted in Figure 9.

Figure 9 indicates that the heat treatment of 200 °C produced the flattest support rings, with a flatness of approximately 1 μm or less. However, these support rings would not be acceptable for applications that require support rings of pure gold. The support rings heat treated at 100 °C all had a flatness better than 2 μm and did not exhibit any interdiffusion when viewed with an optical microscope at 100× magnification. Therefore, a heat treatment at 100 °C would be recommended for applications that require flat support rings of pure gold. Note that the optimum heat treating temperature to produce the flattest support rings that do not exhibit noticeable interdiffusion probably lies between 100 °C and 200 °C.

Figure 10 graphs the flatness of each of the support rings from the mandrel for which the gold and copper were separated by a nickel strike layer. The data points labeled "Ni-Au" represent the support rings machined from the section of the mandrel that did not have an overcoat of nickel and copper on top of the plated gold. The data points labeled "Ni-Au-Ni" represent the support rings machined from the section of the mandrel for which an overcoat of nickel and copper was plated on top of the gold. Once again, the dashed green line represents the specification of 2 μm flatness, and the data points that fall below this line correspond to support rings that meet the specification.

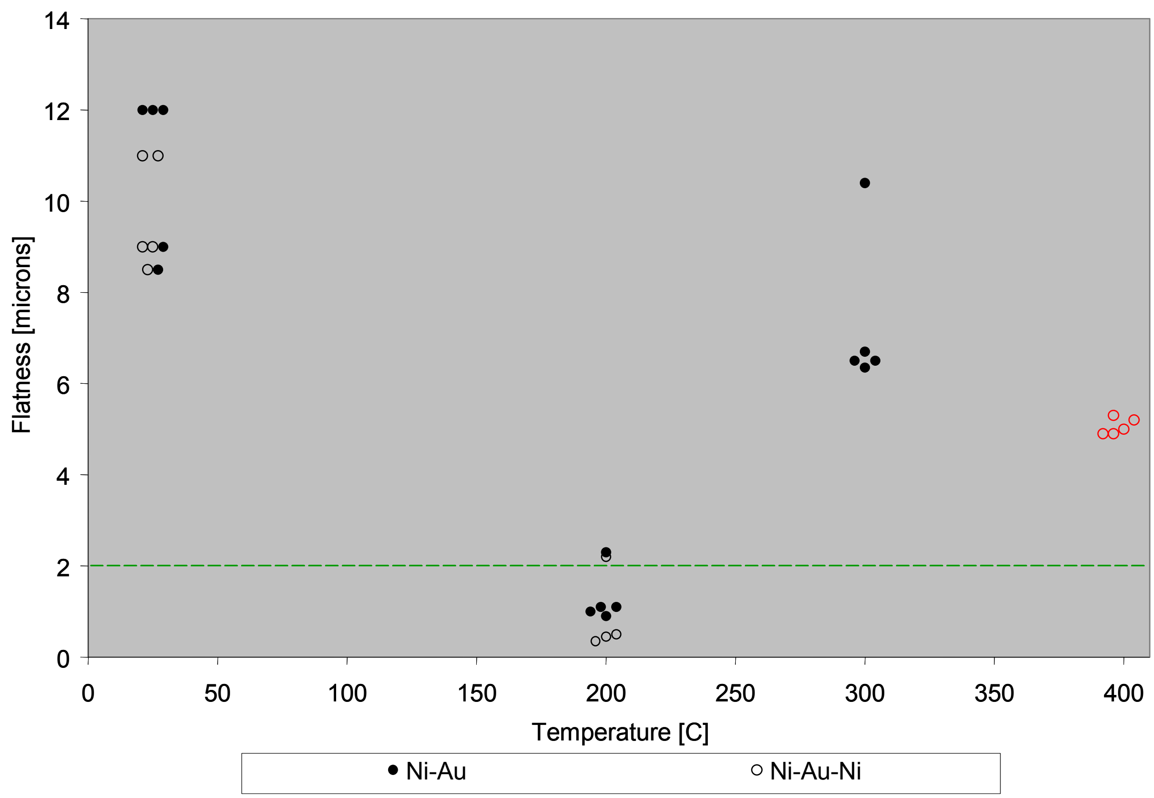

Figure 10. Flatness measurements for each of the rings made from the mandrel with nickel between the copper and the gold

Figure 9 reveals that the support rings with the nickel strike that did not receive any heat treatment had flatness errors ranging from just over 8 μm to 12 μm. There are several possible reasons why the support rings from the mandrel with the nickel strike had larger flatness errors than those from the mandrel with the gold deposited directly onto the copper. Recall that the layer of gold on the mandrel with the nickel strike was only 78 μm, compared to 100 μm on the other mandrel. If the amount of residual stress is the same, a thinner ring will warp more than a thicker ring. It is also possible that the gold plated onto the nickel strike simply achieved a state of greater residual stress than the gold plated directly onto the copper. A greater amount of residual stress would cause a larger degree of warping upon removal of the rigid copper support structure.

One of the sets of support rings with a nickel and copper overcoat on top of the gold layer was heat treated at 396 °C. These data points are plotted in red in Figure 10, because these rings do not exhibit clean surfaces after etching away the copper and the nickel. Dark brown spots appear on the surface that was adjacent to the overcoat layer. The opposite surface appears to be clean. This contamination would make these support rings unacceptable for applications that require support rings of pure gold.

Figure 10 indicates that of the heat treating temperatures tested, a heat treatment of 200 °C produced the flattest support rings. Of the ten support rings heat treated at 200 °C, seven had a flatness of 1.1 μm or better. Of the remaining three rings, two had a flatness of 2.3 μm or better, and the other was bent during handling and is not included in the data. Therefore, a heat treatment at 200 °C is appropriate for producing support rings with a flatness of approximately 2 μm. Note that the optimum heat treating temperature to produce the flattest support rings probably lies somewhere between 25 °C and 300 °C, and further experiments would be required to identify the optimum temperature.

It is important to note that although these experiments appear to indicate that it is not necessary to use a nickel strike between the gold and the copper, there may by situations in which a nickel strike is required. Figure 9 appears to indicate that relatively flat support rings can be obtained without any type of heat treatment. However, there may be occasions in which support rings may be subject to processes that induce additional stresses in the gold prior to etching away the copper. These processes could include the machining of additional features using an endmill or other type of tool whose cutting edge is not nearly as sharp as a single point diamond cutting tool. Machining with a tool of finite cutting edge radius is known to induce stresses into workpieces that cause them to warp when they are removed from their fixtures. In these cases, it may be beneficial to remove these stresses prior to freeing the gold from the rigid copper support structure using a heat treatment of 200 °C or higher. In a case such as this, a nickel strike layer between the copper and the gold may be required to prevent interdiffusion.

These experiments did not reveal any significant effect of the copper overcoat layer on the flatness of the support rings. However, support rings produced with a layer of copper (or nickel and copper) on top of the plated gold did not exhibit any burrs. Any burr produced during the milling process formed at the surface of the overlay layer, which kept the gold layer flat. Conversely, support rings that were milled without this sacrificial copper overlay exhibited burrs of up to 10 μm formed during the milling process.

Reprocessing of Warped Washers

The manufacturing strategy discussed above can mass produce batches of up to 100 support rings per mandrel. As is the case with most batch processing techniques, it is inevitable that some of the parts produced will not meet the specifications. For example, some support rings in a batch may have a flatness error exceeding the specification of 2 μm. Rather than simply discarding these parts, it is possible to flatten them out, so that they can be used in targets.

Flattening of warped support rings can be accomplished by squeezing them between two platens during a heat treatment. Two of the platens that are illustrated in Figure 3 were prepared by diamond turning the upper face and then plating them with several microns of nickel. Three warped support rings were placed onto one of the platens, and the other platen was placed on top to squeeze them flat. This platen-ring-platen sandwich was then placed in the furnace, heat treated at 200 °C for 60 minutes, and then allowed to cool overnight. Using this method, a group of rings was reprocessed to improve the flatness from 9 μm - 11 μm to 1 μm - 3 μm. Figure 11 plots Wyko data for an example support ring before and after heat treatment between the platens. Note that the flatness of this support ring has been improved from 9 μm to 1.5 μm.

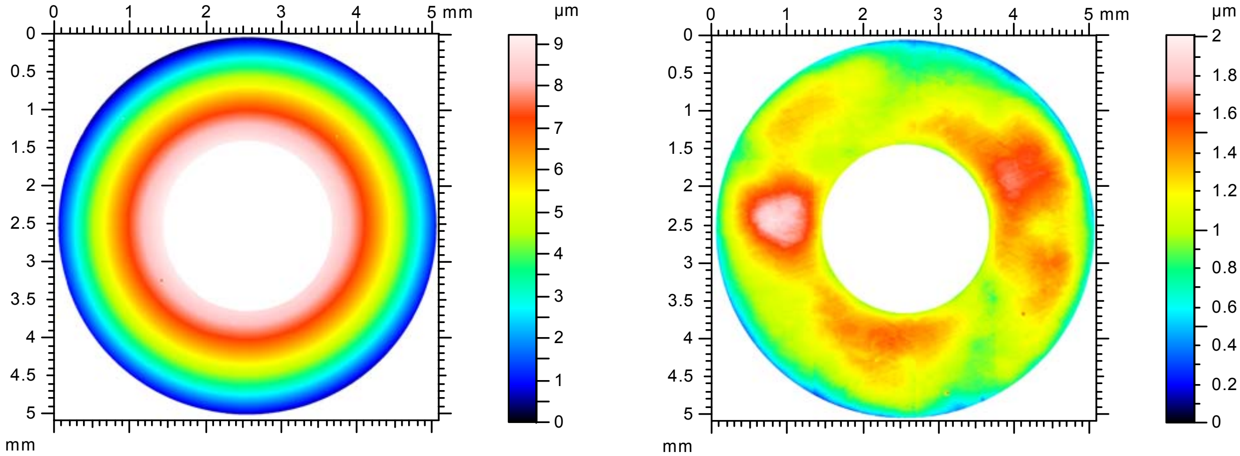

Figure 11. Profile of a support ring before (left) and after (right) heat treatment between platens

PRODUCTION OF PRECISION SUPPORT RINGS FOR LASER TARGETS

This manufacturing strategy has been successfully used to fabricate precision support rings for EOS, RadF, HyDiv, and SEA targets. Two mandrels were processed to create these support rings, as illustrated in Figure 12. The support rings created in this initial production run had a thickness of 200 μm. The left side of the figure depicts a mandrel that has been milled with 47 support rings for RadF targets, 15 support rings for HyDiv targets, 24 support rings with a groove machined across the diameter for HyDiv targets, and 22 support rings for SEA targets. The right side of the figure depicts a mandrel that has been milled with 58 standard EOS support rings, and 5 prototype support rings for EOS targets for NIF that incorporate a stem that is used to mount a mirror onto the target package.

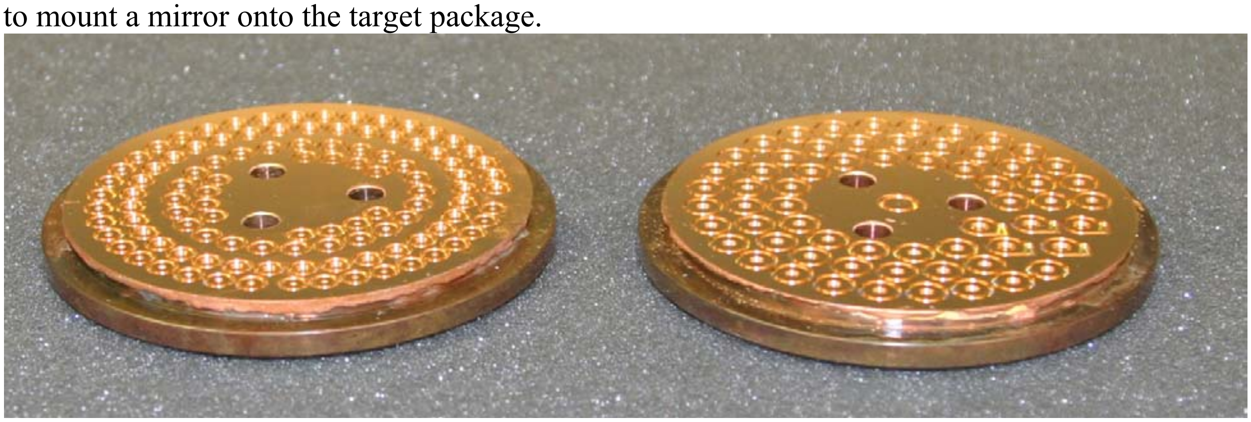

Figure 12. Mandrels that have been milled with patterns of support rings

After placing these mandrels into an acid solution to remove the copper, the 171 support rings were collected. A photograph of some of the finished support rings appears in Figure 13. Approximately twenty of the support rings were selected at random and were measured with the Wyko optical profiling system and with a measuring microscope. Each of the support rings measured had a flatness better than 2 μm, and the inner and outer diameters were consistent to better than 2 μm. Therefore, each of the components measured meets the specifications and will be used for laser targets that will be shot on the Omega laser and on NIF.

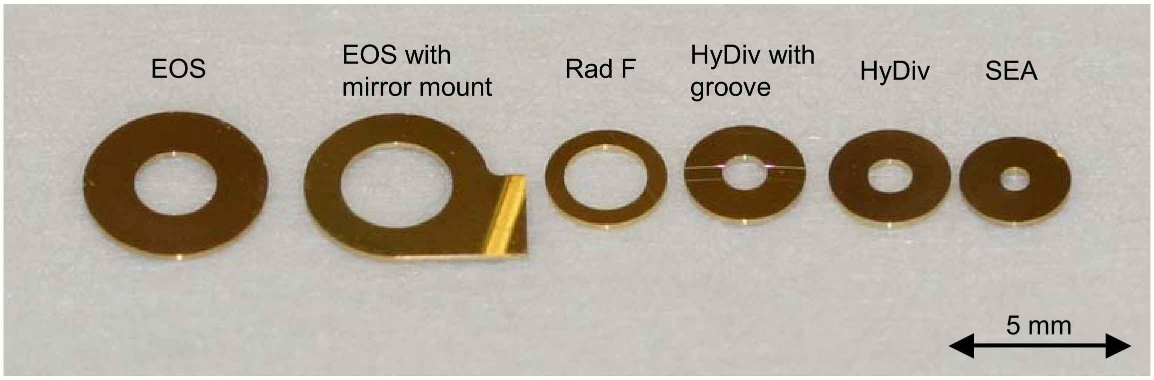

Figure 13. Six different types of support rings produced in the first production run

CONCLUSIONS

A research effort performed by the Target Fabrication Group has developed a method for producing precision, meso-scale gold support rings for laser targets. These washer-shaped precision rings are a fundamental support structure for many different types of targets, and they must be very precise to achieve the required overall precision in the finished laser targets. Previously, vendors have been unable to provide adequate support rings, which has compromised the timely manufacture and delivery of several types of targets. To eliminate the risk to the production schedule, a method has been developed for manufacturing precision support rings using a combination of electroplating, diamond turning, milling, and etching. The initial production run successfully produced 171 as-specified support rings for 6 different types of targets. These support rings meet the specifications of a flatness of better than 2 μm and precision of the inner diameter of better than 2 μm. A batch of precision support rings can be produced in a matter of days, and they are not limited to an axisymmetric shape. Thus, this new method will not only increase the overall precision of laser targets and eliminate potential compromises to the timely delivery of targets, but it will also allow greater complexity in the design of target components.

RECOMMENDATIONS

This research effort has developed a manufacturing method that produces precision target support rings with flatness of better than 2 μm. For a typical support ring with a diameter of 5 mm, this equates to a ratio of flatness to diameter of 0.04%. However, occasions may arise in which target components require support rings or similar planar components with an even smaller flatness. To achieve improved flatness, additional research must be performed to optimize the electroplating and heat treating processes.

This study included a brief investigation of the parameters used to electroplate the gold onto the copper mandrel [1]. However, due to time and budget constraints, it was not possible to optimize the plating process. Further research must be performed to determine the process conditions that minimize the residual stress in the plated gold. Parameters that could be varied to reduce the residual stress include the composition of the plating solution, current density, temperature, and agitation method. These parameters must be optimized for both gold plated directly onto copper and for gold plated onto a nickel strike layer.

This study also included a limited number of tests on the effects of heat treating temperature on the gold prior to etching away the copper support mandrel. Heat treating the gold is critical in situations in which the gold cannot be electroplated with minimized residual stress, or the machining of the components in the plated gold induces additional residual stresses. This study revealed that the optimum heat treating temperature that produces the flattest support rings that do not exhibit noticeable interdiffusion for a copper mandrel plated with gold must lie somewhere in the range between 100 °C and 200 °C. Likewise, the optimum heat treating temperature for a mandrel with a nickel strike layer between the copper and the gold must lie somewhere in the range between 25 °C and 300 °C. In both of these cases, the specific value of the optimum temperature is not known. In the production run that yielded the first target support rings, a heat treating temperature of 100 °C was used. However, this value is not necessarily the optimum choice, and a slightly higher temperature may produce even flatter washers. Further tests are required to narrow down the temperature ranges to determine the specific values for the optimum heat treating temperatures. Further tests may reveal an optimum temperature that most efficiently relieves residual stresses in the gold prior to freeing the components from the copper support mandrels, which would improve the flatness of the support rings even further.

Note that this research effort has identified a manufacturing process to produce precision target support rings that exceed current requirements. However, because of the continually evolving nature of laser target design and fabrication, the specifications of future target components will inevitably become more demanding, and the fabrication of these future targets with the required level of precision may require support rings that are even more precise than those developed in this research. Achieving an improved level of precision will require this additional research.

ACKNOWLEDGEMENTS

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REFERENCE

[1] Robles, Rudy. "Plating and Etching Procedures for the Manufacture of Precision Target Support Rings," 2004. Available on the DNT/DMS.